ACCELERATION OF POLARIZED BEAMS USING MULTIPLE STRONG PARTIAL SIBERIAN SNAKES*

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Abstract

Acceleration of polarized protons in the energy range of 5 to 25 GeV is particularly difficult since depolarizing spin resonances are strong enough to cause significant depolarization but full Siberian snakes cause intolerably large orbit excursions. Using a 20 - 30 % partial Siberian snake both imperfection and intrinsic resonances can be overcome. Such a strong partial Siberian snake was designed for the Brookhaven AGS using a dual pitch helical superconducting dipole. Multiple strong partial snakes are also discussed for spin matching at beam injection and extraction.

INTRODUCTION

Accelerating polarized beams requires the control of both the orbital motion and spin motion. The evolution of the spin direction of a beam of polarized protons in external magnetic fields, such as those existing in a circular accelerator, is governed by the Thomas-BMT equation [1],

$$\frac{d\vec{P}}{dt} = -\frac{e}{\gamma m}\left[G\gamma\vec{B}_T + \left(1+G\right)\vec{B}_L\right]\times\vec{P},$$

where the polarization vector P is expressed in the frame that moves and rotates with the particle's velocity. This simple precession equation is very similar to the Lorentz force equation:

$$\frac{d\vec{v}}{dt} = -\frac{e}{\gamma m}\vec{B}_T\times\vec{v}\ .$$

Comparison of these two equations readily shows that, in a purely vertical field, the spin rotates Gγ times faster than the orbital motion. Here G=1.7928 is the anomalous magnetic moment of the proton and γ = E/m. Gγ gives the number of full spin precessions for every revolution and is also called the spin tune ν_{sp}.

The acceleration of polarized beams in circular accelerators is complicated by the presence of numerous depolarizing spin resonances. During acceleration, a spin resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields are encountered. There are two main types of spin resonances corresponding to the possible sources of such fields: imperfection resonances, which are driven by magnet errors and misalignments, and intrinsic resonances, driven by the focusing fields. The strengths of both types of resonances increases with beam energy.

The resonance condition for imperfection depolarizing resonances arise when $\nu_{sp} = G\gamma = n$, where n is an integer. Imperfection resonances are therefore separated by only 523 MeV energy steps. The condition for intrinsic resonances is $\nu_{sp} = kP \pm \nu_y$, where k is an integer, ν_y is the vertical betatron tune and P is the super-periodicity.

In medium energy accelerators such as the Alternating Gradient Synchrotron (AGS) depolarizing spin resonances are strong enough to completely depolarize the beam. This can be seen from the Froissart-Stora formula of expected depolarization for passage through an isolated spin resonance for a beam with Gaussian transverse distribution:

$$\frac{P_{final}}{P_{initial}} = \frac{1-\pi\left|\varepsilon\right|^2/\left(6\alpha\right)}{1+\pi\left|\varepsilon\right|^2/\left(6\alpha\right)},$$

where ε is the resonance strength for a particle with a Courant-Snyder invariant of 10 π mm mrad. For the AGS acceleration rate of 50 GeV/s ($\alpha = 4\times10^{-5}$) a resonance strength of 0.009 leads to complete depolarization. Typical resonance strengths in the AGS are between 0.0001 and 0.02 and therefore most of the resonances are causing significant depolarization.

All imperfection resonances can be overcome by introducing a local spin rotator (“partial Siberian snake”) that effectively increases the strength of all imperfection resonances to the point that they all introduce complete spin flip. The resonance strength caused by a spin rotator that rotates the polarization by δ around a horizontal direction is:

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$$\varepsilon_{ps} = \delta / (2\pi).$$

The present AGS partial snake rotates the spin by 9°, which corresponds to a resonance strength of 0.025, which is much larger than the imperfection resonance strengths in the AGS. Note that with a partial Siberian snake the closest approach of the spin tune to an integer value is equal to ε_{ps}. This is a special case of the formula for the spin tune of a ring with a partial Siberian snake:

$$\nu_{sp} = \frac{1}{\pi}\cos^{-1}\left(\cos(\delta/2)\cos(\pi G\gamma)\right).$$

STRONG PARTIAL SIBERIAN SNAKE

With a strong enough partial snake it should be possible to increase the closest approach of the spin tune to an integer enough that it becomes possible to place the fractional part of the betatron tune and therefore the intrinsic resonance inside this gap. For example a 20 % partial snake would leave a gap of 0.1 – large enough to allow for operation with a practical fractional betatron tune of 0.95 as has been demonstrated at the AGS after careful orbit correction. Tracking calculations revealed that for strong intrinsic resonances this betatron tune window is reduced further by higher order depolarizing resonances that are similar to snake resonances. The strongest higher order resonance is located in the middle of the gap but still leaves sufficient room for placing the betatron tune.

If it is possible to build such a strong partial Siberian snake a single device would eliminate depolarization from all spin resonances and allow for polarized proton acceleration in medium energy accelerators. For the AGS the challenge amounts to building a 36° spin rotator with a maximum length of 2.6 m and internal orbit excursion of less than about 4 cm. A solenoid spin rotator would have to have a field of at least 7 Tesla, which would lead to an unacceptable level of orbit coupling and also to strong coupling spin resonances. The most compact solution consists of a 3 Tesla helical dipole with variable pitch. The two ends have a helical pitch that is twice the helical pitch at the center. This field profile allows for a compact matching of the outside orbit to the helical orbit

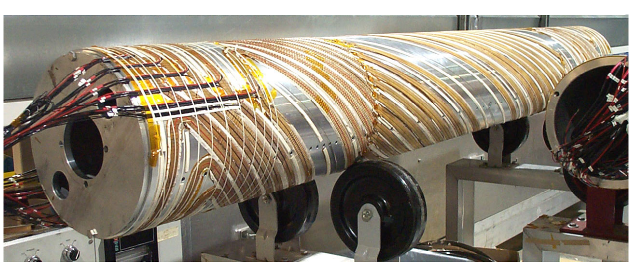

Figure 1: Helical windings of the super-conducting strong Siberian snake for the AGS

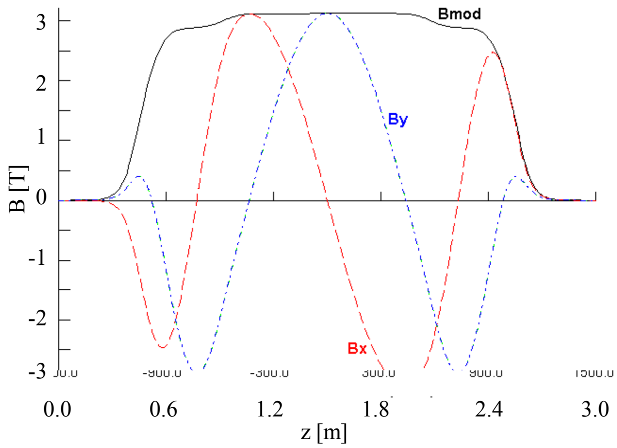

Figure 2: Magnetic field profile of the super-conducting strong partial Siberian snake. Bmod is the magnitude of the magnetic field.

inside the magnet. Figure 1 shows the picture of one of the coils of the super-conducting helical dipole presently being constructed the BNL Super-conducting Magnet Division. Figure 2 shows the calculated magnetic field profile.

MULTIPLE PARTIAL SIBERIAN SNAKES

With a partial Siberian snake the stable spin direction reverses direction at all imperfection resonances but is very close to the vertical direction at half-integer values of $G\gamma$ as long as the partial snake is relatively weak. It is therefore possible to inject and extract vertically polarized beam at these energy values without much loss of polarization. At the AGS injection and extraction occurs at $G\gamma = 4.5$ and 46.5, respectively.

For a strong partial snake, however, polarization loss at injection and extraction is not negligible anymore. A 20% snake will lead to a 10% polarization loss due to this spin direction mismatch. This could be solved with appropriate spin rotators in the injection and extraction beam lines. However, a single additional partial snake located in the AGS can provide the spin direction matching at injection and extraction and also increase the effective partial snake strength if its position is chosen properly.

The location and the precession axis direction of multiple partial Siberian snakes has to be chosen very carefully to maintain control of the spin tune as is the case for multiple full Siberian snakes. For practical partial Siberian snakes the precession axis direction is always very close to longitudinal, which leaves only the location and strength of the partial snakes as free parameters.

The spin tune for two partial Siberian snakes with rotation angle δ_1 and δ_2 and separated by one third of the ring is given by:

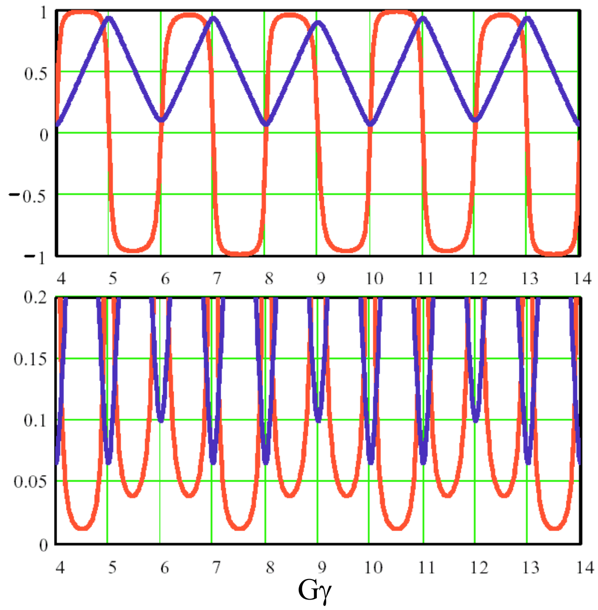

Figure 3: Top figure shows spin tune (blue) and vertical component of the stable spin direction (red) for a 5% and 15% partial Siberian snake separated by 120° azimuthal angle as a function of Gγ. The bottom figure shows the deviation from an integer for the same quantities.

$$\nu_{sp} = \frac{1}{\pi}\cos^{-1}\left(\cos\left(\frac{\delta_1}{2}\right)\cos\left(\frac{\delta_2}{2}\right)\cos(\pi G\gamma) - \sin\left(\frac{\delta_1}{2}\right)\sin\left(\frac{\delta_2}{2}\right)\cos\left(\frac{\pi}{3}G\gamma\right)\right)$$

Separating the two partial snakes by one third of the ring is of particular interest since it will introduce a periodicity of three units in the spin tune dependence on Gγ. Since both the super-periodicity of the AGS (12) and the vertical betatron tune (~9) are divisible by three the spin tune will be the same at all intrinsic resonances. For Gγ = 3n $\nu_{sp} = (\delta_1+\delta_2)/\pi$. With both snakes at equal strength $\nu_{sp} = \delta/\pi$ effectively doubling the strength of the partial snakes. At the injection and extraction energies, for which Gγ = 3n + 1.5, the two snakes cancel. The polarization direction in the AGS is therefore exactly vertical and no polarization is lost due to spin direction mismatch.

Even using the presently installed normal-conducting helical partial Siberian snake with a rotation angle of 9° [2,3] a very substantial reduction of the injection and extraction spin mismatch can be achieved. At the same time the effective strength of the partial snakes at the intrinsic resonances is significantly increased. Figure 3 shows the spin tune and the vertical component of the spin direction in the AGS with two partial snakes with rotation angles of 9° (5% partial snake) and 27° (15% partial snake), respectively.

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